

A STUDY OF RESIDUAL STRESSES IN
WELDED STRUCTURES

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CHAO-CHIEN HAO

B. S., Chiao Tung University, Shanghai, 1936

M. S., University of Illinois, 1943

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A STUDY OF RESIDUAL STRESSES IN WELDED STRUCTURES

The thesis is a report of an investigation to determine the effect of residual stresses upon the behavior of structural members. The behavior of members under static loads was determined by analysis and by tests; their behavior under repeated loads was determined by fatigue tests.

A brief explanation of the cause of residual stresses and their magnitude, followed by a review of some theoretical investigations to determine the distribution of residual stresses in a welded plate, is given in Chapter II. The residual stresses in a welded assembly is caused by the plastic deformation due to the local intensive heating of the weld. The residual stress in a welded seam may as high as the yield point. The theoretical investigations reviewed are the elastic theory by Grüning¹, the plastic theory by Boulton and Lance Martin², and by Rodgers and Fletcher³. The writer gives an analysis based on the same assumptions as Grüning, using Fourier's series. The results agree with those obtained by Grüning.

An analytical method of determining the behavior under static loads of a plate with a longitudinal butt weld on the center line, is given in Chapter III. Its application is illustrated by an example involving the determination of the behavior under static load of a 10-in. plate with a longitudinal butt weld on the center line. The analysis is based upon the following assumptions: (1) A plane remains a plane during the application of loads, and (2) The stress at any point increases according to the stress-strain curve of the material at the point.

¹ Grüning: Die Schrumpfspannungen beim Schweißen; Stahlbau, July 6, 1934; pp. 110-112.

² Boulton and Lance Martin: Residual stresses in arc-welded plates; Proc. Inst. of M. E., Vol. 133, pp. 295-347; London, 1936.

³ Rodgers and Fletcher: The determination of internal stresses from the temperature history of a butt-welded plate; Am. Welding Jnl., V. 17, No. 11; Nov. 1938; pp. WRS 4-7.

This analysis indicates that if the plate is stretched, the stress does not exceed the yield point in any area until the yield point of the plate as a whole has been reached. The ultimate strength of the plate depends upon the ductility of the weld and the heat-affected base metal. The writer's prediction that a longitudinal weld in a plate will not break at an elongation equal to the maximum elongation for the weld acting as a separate strip is supported by the results of tests. The base metal near the weld apparently enables it to elongate more than it does when it is a separate strip. The conclusions reached through this analysis is given in the summary of results at the end of this abstract.

Two series of tests made to verify the preceeding analysis are reported in Chapter IV. The tests were planned to determine : (1) The residual stresses in a specimen made of two plates of equal width connected by a longitudinal butt weld, (2) The physical properties of different parts of such specimens, and (3) The behavior of similar specimens containing residual stresses when tested statically, in order to compare the actual behavior with the behavior indicated by the analysis. Four specimens were used for each series. The specimens used for tests of Series I had a section of 5-in. by $\frac{7}{8}$ -in., and those used for the tests of Series II had a section of 12-in. by $\frac{5}{8}$ -in. They were made of A.S.T.M., A-7 steel. One specimen of each series was used to determine the residual stresses by the method of relaxation, and to determine the physical properties by tension tests. One specimen of each series which had no welds on the center line was used as a control specimen. Other specimens were tested statically.

Results of tests indicate that the maximum residual stress was in the weld, and the weld and the adjacent heat-affected metal had significantly higher yield point, slightly higher ultimate strength, and lower elongation and reduction of area than the parent metal. The maximum residual stress in Specimen No. 7, Series I, was 34,000 psi. tension in the weld. The weld of the same specimen had a yield point of 50,600 psi., and an ultimate strength of 67,500 psi. The elongation in 8 in. was 10.0 per cent and the reduction of area, 20.4 per cent. The maximum residual stress in Specimen No. 2, Series II, was

48,400 psi. tension in the weld. The weld of the same specimen had a yield point of 52,300 psi., and an ultimate strength of 72,200 psi. The elongation in 8 in. was 10.5 per cent and the reduction of area, 22.0 per cent.

For Series I, Specimen No. 0, which was the only specimen without a weld, developed a yield point of 31,600 psi. and an ultimate strength of 65,470 psi. The elongation in 8 in. was 33.4 per cent and the reduction of area, 36.2 per cent. Specimen No. 3 developed a yield point of 38,000 psi., and an ultimate strength of 67,700 psi. The elongation in 8 in. was 17.3 per cent and the reduction of area, 21.8 per cent. Specimen No. 6 developed a yield point of 38,400 psi., and an ultimate strength of 67,000 psi. The elongation in 8 in. was 17.4 per cent and the reduction of area, 21.0 per cent. The yield point of Specimen No. 7 as determined by analysis was 38,500 psi. and the ultimate strength of the same specimen was 65,500 psi.

For Series II, Specimen No. 0, which was the only specimen without a weld, developed a yield point of 37,400 psi. and an ultimate strength of 67,200 psi. The elongation in 8 in. was 38.3 per cent and the reduction of area, 34.6 per cent. Specimen No. 1 developed a yield point of 38,800 psi. and an ultimate strength of 70,000 psi. The elongation in 8 in. was 27.3 per cent and the reduction of area, 26.7 per cent. Specimen No. 3 developed a yield point of 39,800 psi. and an ultimate strength of 69,000 psi. The elongation in 8 in. was 27.0 per cent and the reduction of area, 26.1 per cent. The yield point of Specimen No. 2 as determined by analysis was 38,500 psi. and the ultimate strength of the same specimen was 66,600 psi.

The stress-strain curves for the welded specimens determined by tests, and those determined by analysis, show remarkable resemblance. The deformation was much more for the welded specimens than for the control specimens (plates without weld) at loads below the yield point; but was less for the welded specimens than for the control specimens at loads above the yield point. The welded specimens had a higher yield point, higher ultimate strength, lower elongation and lower reduction of area than the control specimens.

Tests of plates with circular welded seams are reported in Chapter V. Three 12-in. by $\frac{5}{8}$ -in. by 20-in. plates used to determine the residual stresses by the method of relaxation, each had a circular welded seam of 4-in., 6-in., and 8-in. diameter, respectively. Three specimens used for the static tests had similar circular welded seams. All of these specimens were made of A. S. T. M., A-7 steel.

The residual stresses in the three plates determined by the method of relaxation revealed that there were nearly equal bi-axial tensile stresses in the weld of all plates and also in the portion of the plates enclosed by the welded seam for plates with a circular welded seam of smaller diameter. These residual stresses were of the order of the yield point of the base metal. The residual stresses at points near the edges of the plates were predominantly uni-axial compression parallel to the edges.

Specimen No. 1, which had a 4-in. diameter circular welded seam, developed a yield point of 35,700 psi. and an ultimate strength of 67,500 psi. The elongation in 2 in. was 48.0 per cent and the reduction of area, 34.1 per cent. Specimen No. 2, which had a 6-in. diameter circular welded seam, developed a yield point of 37,400 psi. and an ultimate strength of 70,500 psi. The elongation in 2 in. was 33.4 per cent and the reduction of area, 23.1 per cent. Specimen No. 3, which had an 8-in. diameter circular welded seam, developed a yield point of 37,600 psi. and an ultimate strength of 71,200 psi. The elongation in 2 in. was 32.7 per cent and the reduction of area, 22.7 per cent.

Specimens Nos. 2 and 3 developed a slightly higher yield point and ultimate strength than the coupon specimens, but Specimen No. 1 developed lower yield point and ultimate strength. However, all specimens had a higher ultimate strength than the control specimen No. 0 of Series II, Chapter IV, which was made of steel of same heat and had the same dimensions as specimens with circular welded seams. All specimens failed outside the circular welded seam.

Fatigue tests, made to determine the effect of residual stresses upon the fatigue strength of plates with longitudinal

butt welds, are described in Chapter VI. All fatigue specimens had a section of 5-in. by $\frac{7}{8}$ -in. and had a longitudinal butt weld on the center line, except two control specimens, which had no welds. All specimens were made of A. S. T. M., A-7 steel.

For the preliminary tests, one specimen was tested in the as welded condition. It failed at 253,000 cycles on a stress cycle of 0 to 30,000 psi. tension. The other three specimens had their surfaces planed and draw filed before being tested. The stress cycles for these three specimens were $\pm 26,000$, $\pm 20,000$ and $\pm 16,000$. They failed at 19,000, 213,000, and 195,000 cycles, respectively.

For the final tests, all specimens had their surfaces planed and draw filed before being tested. The stress cycles for the two specimens without a weld were: $\pm 22,000$ and $\pm 20,000$ psi. They failed at 428,000 and 776,000 cycles, respectively. The stress cycles for the four welded specimens not stress-relieved were: $\pm 20,000$, $\pm 18,000$, $\pm 16,000$ and $\pm 16,000$ psi. They failed at 187,000, 1,105,000, 961,000 and 547,000 cycles, respectively. The stress cycles for the four specimens stress-relieved by pulling to the yield point were: $\pm 22,000$, $\pm 20,000$, $\pm 20,000$, and $\pm 16,000$ psi. They failed at 84,900, 197,000, 465,000, and 1,670,000 cycles, respectively.

The results of the entire investigation are given in the summary of results.

SUMMARY OF RESULTS

PLATES CONNECTED WITH LONGITUDINAL BUTT WELDS. STATIC LOADS.

The analysis of specimens made of two A. S. T. M., A-7 steel plates of equal width connected by a longitudinal butt weld resulted in the following conclusions, all of which are supported by the tests.

1. The residual stresses due to welding do not in themselves affect the yield point or the ultimate strength of the specimen as a whole.

2. The ultimate strength of the specimens as a whole depends upon the ductility of the weld metal and of the heat affected base metal.

3. The yield point of the specimen is equal to the average yield point of the material in the specimen.

4. Due to the fact that the weld and the heat-affected base metal have a higher yield point than the unaffected base metal, the yield point of the specimen as a whole is always higher than that of the unaffected base metal.

5. For a given applied average stress below the yield point of the base metal, the specimen deforms much more than the plate without a weld. This is attributed to the presence of residual stresses. For a given applied average stress above the yield point of the base metal, the specimen deforms less than the plate without a weld.

6. The effect of the longitudinal weld upon the yield point, ultimate strength, and deformation at loads above the yield point of the base metal (including elongation at failure), depends upon the width of the plate, the wider the plates, the less the effect.

PLATES WITH CIRCULAR WELD SEAMS. STATIC LOADS.

Tests of plates with circular butt weld seams appear to justify the following statements:

1. Plates containing circular welded seams had bi-axial residual stresses equal, approximately, to the yield point of the base metal.

2. The circular welded seam in the plates did not impair their ultimate strength.

PLATES CONNECTED WITH LONGITUDINAL BUTT WELDS. FATIGUE TESTS.

The rather limited number of tests does not justify drawing quantitative conclusions. However, the following definite trends are shown.

1. Plates with longitudinal butt welds had a somewhat lower fatigue strength than similar plates without welds. This was true for specimens that had been stress-relieved by pre-stressing to the yield point as well as for specimens that had not been stress-relieved.

2. Welded plates with residual stresses had a slightly lower fatigue strength than those stress-relieved by pulling to the yield point.

The tests appear to justify the conclusion that residual stresses resulting from longitudinal butt welds connecting plates reduce the fatigue strength of the welded plates somewhat, but the reduction is not great if the welds are free from flaws.

VITA

Chao-Chien Hao was born in Hwai-An, Kiangsu, China, on April 3, 1914. He graduated with honor from the Chiao-Tung University, Shanghai, in June 1936, receiving the degree of B.S. in C.E. He served the Chinese Ministry of Communications since he graduated from the college. He came to the United States on leave in 1941, to visit the Bridge Division of the Public Roads Administration in Washington, D. C.. He attended the University of Illinois since September 1942, receiving the degree of M.S. in C.E. in June 1943. He was elected associate member of the Sigma Xi in April 1943.

